PRACTICAL SUGGESTIONS RESPECTING

THE VENTILATION OF BUILDINGS.

A REPORT TO THE STATE BOARD OF HEALTH.

BY JOHN H. KELLOGG, M. D., MEMBER OF THE MICHIGAN STATE BOARD OF HEALTH, BATTLE CREEK.

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Gentlemen:—In obedience to your request, I herewith present in brief form a few suggestions and fundamental principles which it is believed may be found of service in arranging the ventilating system of public and private buildings. The sole effort has been to embody, in as brief and lucid a form as possible, the information which the writer has gathered during some years of study of the subject, and such facts as he has gleaned from his own experience in planning and superintending buildings of some size for hospitals and other purposes. The only recommendation offered for the plans and principles suggested is that they have borne the test of practical experiment in a satisfactory manner, which cannot be said respecting all the schemes for the warming and ventilation of buildings which have been offered in works on sanitary subjects published within the last score of years. In justice to himself, the writer ought to say that he has not undertaken to make this paper exhaustive, or anything more than what its title indicates; neither has he undertaken to enter the field which properly belongs to the architect, but rather to present simply such suggestions and theories as he has himself found of practical value, and which are susceptible of general application, omitting altogether the minor details, which, however necessary to the adaptation of a general plan or principles to any particular case, are likely to be of little service except in the special conditions to which they are specially adapted. Seeking, then, to avoid as much as possible redundancy of language and circumlocution in methods of presentation, let us begin at once the discussion of the things most essential in a correct scheme for the proper ventilation and heating of a building.

First of all, it may be stated that the ventilation and heating of a building must be considered together, for a successful working of each will depend upon the conditions of the other. It needs no argument to impress the fact that the amount of heat to be furnished in any given instance must depend very largely upon the amount of fresh air to be supplied per hour or minute. If the air of a room is to be changed four times per hour, certainly a proportionately larger quantity of fuel must be consumed than if the air is to be changed but once an hour.

The air supply of a room or building is generally determined by its size rather than by the number of persons by which it is to be occupied. This is certainly not a scientific method. A large room, occupied by but one or two persons might possibly admit through cracks, about windows and doors, and through its porous walls a sufficient air supply; while a small room, crowded with people, would require a very large provision for the supply of fresh air. The first thing, then, to be considered in the study of the ventilation of a room or building is the number of persons who are to occupy the space under consideration.

According to the most eminent sanitary authorities of England, each

healthy adult person requires not less than three thousand cubic feet of air per hour. This statement is based upon careful experiments, which showed that if the normal quantity of carbon di-oxide contained in the atmosphere, which is two parts to every five-thousand parts of air, is increased to three parts in five thousand of air, the limit of tolerable impurity is reached; that is, if the amount of CO_2 is increased by respiration to a larger proportion than that stated, namely, three parts in five thousand, the air thus contaminated becomes productive of disease. It must not be supposed that the poisonous properties of such air are due to the chemical compound CO_2. Air may contain a much larger proportion of CO_2 provided this compound is derived from purely chemical sources, without injury being apparent. But when the CO_2 is furnished by the respiration of animals, there is associated with it a subtle poison, which has been shown by the eminent physiologist, Prof. Brown-Sequard, to be one of the most powerful poisons known, exceedingly minute quantities being sufficient to produce death.

A little computation based upon the experiments referred to will show that Dr. Parke's figures are certainly not extravagant. With each breath, each human being exhales into the air one cubic inch of carbon di-oxide, and a definite amount of organic poison associated with it. As air naturally contains two cubic inches of carbon di-oxide in every five thousand cubic inches of air, and as an additional cubic inch of CO_2, or three cubic inches in five thousand cubic inches of air is the limit of safety, it is evident that each breath renders unfit for further use, five thousand cubic inches, or approximately, three cubic feet of air. The average person breathes eighteen times per minute; consequently, each person spoils or renders unfit for further use, 3×18, or 54 cubic feet of air per minute. 54×60 gives us, as the amount of air which each person contaminates per hour, 3,240 cubic feet, a slight excess over the amount named by Prof. Parkes. Some other authorities place the line of dangerous contamination at a somewhat higher point, and consequently they require a smaller amount of air. Avoiding either extreme, we may place the amount of air required per hour for each healthy person, at about 2,400 cubic feet. It must be understood, however, that this rule applies to healthy persons only, and is not applicable to hospitals or buildings occupied by infirm or sick persons. For such institutions, and for manufacturing establishments in which the air may be contaminated by chemical or other processes, at least double the amount named, or 5,000 cubic feet of air per hour must be supplied. In any given case then, to ascertain the amount of air required per hour, we have only to multiply 2,400 or 5,000 as the case may be, by the number of persons to be supplied with air. The number of persons taken should be the maximum rather than the minimum number which the room or building is calculated to accommodate, for the evident reason that the capacity of a ventilating shaft, duct or opening, may be easily diminished, but cannot be so readily increased.

Having determined the amount of air required in any given case, the following important practical points remain to be determined:—

1. The circulation of the fresh air.
2. The area of fresh-air inlets.
3. The area of foul-air outlets.
4. The location of foul-air outlets.
5. The construction and location of foul-air ducts.
6. The location, sectional area and height of ventilating shafts.

7. The question of artificially assisting the draft by means of a pressure or suction fan, or by means of heat in the ventilating shaft.

We will consider each of these several questions in the order named.

1. A room cannot be properly ventilated without an efficient arrangement for the circulation of air. For this there must be for each space to be ventilated at least two openings: one for the admission of fresh air, the other for the removal of impure air. Nothing could be more absurd than the frequently witnessed attempt to ventilate a room by supplying it with a ventilating shaft connected with proper ducts and foul-air openings, but without any provision for a supply of fresh air. Such an arrangement is eminently well calculated to produce dangerous drafts through the opening of windows, and the impression that any attempt at efficient ventilation is liable to result in failure. It is also essential for the proper distribution of the air admitted to a room that the air shall be heated before it enters the room or building, or at the moment of entering.

2. To determine the required area of fresh air inlets, the amount of air required and the velocity at which the air is to travel must be known. Air heated to a temperature of 40° F. above that of the external air will travel at the rate of about five feet a second when entering a room of ordinary height, from which it may escape readily. If the escape of air from the room is assisted by means of an efficient ventilating shaft the velocity of the incoming air may be safely computed as ten feet per second. If the fresh air enters the room at a temperature so high as 120° F. to 150° F. the velocity of the air-current will be increased to 12 or 15 feet per second. Better practical results are obtained by large volumes of moderately heated air, traveling at a moderate speed, than from super-heated air traveling at a high velocity.

Calculating the velocity of the incoming air at ten feet per second it is only necessary to divide the total amount of air required per second by ten and the result will represent the area of free opening required. An allowance of at least forty per cent must be made when the openings are covered by register-plates. For example: Suppose the amount of air needed is 240,000 cubic feet per hour, sufficient to supply 100 persons with the minimum quantity of air. This requires $66\frac{2}{3}$ cubic feet of air per second. Sixty-six and two-thirds divided by 10 is $6.6\frac{2}{3}$. Adding 40 per cent for obstruction of register plate, gives us 9.3 square feet as the combined areas of the register-covered openings for admitting fresh air.

3. The number and location of the fresh-air inlets is not a matter of so great importance as is commonly supposed. If the fresh air enters the room at a temperature 20 to 40 degrees higher than that of the air of the room it will go at once to the ceiling no matter where or how admitted, and will thence gradually diffuse itself through the room, its course being chiefly determined by the location of the windows and of the foul-air-exit openings. I think it preferable that the fresh-air inlet should be in the wall, near the floor, rather than in the floor, as it is by this means better protected against the accumulation of dust and dirt.

In the case of large buildings containing several floors and many rooms or apartments to be supplied with air, it is best not to undertake to carry a separate fresh-air duct to each room, but to equalize the air pressure within the building by leading large ducts to the common hall or corridor of each floor, supplying each room of each floor through open transoms or register plates placed near the ceiling. This arrangement secures a constant supply of pure air in the halls or corridors from which each room

can draw, and establishes a constant current in the direction of individual users of the air, the foul air being directly removed from each separate room by its own duct. This plan secures the greatest possible safety from the dissemination of contagion or the dispersal of any element capable of producing dangerous contamination of the air.

4. Experience has shown that in order to prevent unpleasant draft, the velocity of the air at outlet openings should not be greater than five feet per second. The necessary area of outlet openings is readily obtained then, by simply dividing the total amount of air to be supplied per second by 5. For example, suppose a room to be ventilated is calculated to accommodate thirty persons, each to be supplied with 2,400 cubit feet of air per hour. The aggregate amount of air to be supplied will be 30×2400 or 72,000 cubic feet. Dividing this amount by 3600, the number of seconds in an hour, we have 20 cubic feet as the amount required for each second. Dividing this by 5, the velocity allowable, we have 4, which represents the necessary area for the foul-air outlets in square feet.

It must of course be understood that the figures thus obtained represent actual opening, and not an opening partially obstructed by a grate or register. As before stated forty per cent must be allowed for when the opening is covered by an ordinary register.

As regards the proportion of the area of the foul-air exits to the area of fresh-air inlets, it may be said that outlets should be at least double the area of the inlets, since a velocity of 10 or 15 feet per second may be allowed without injury or inconvenience at the inlet although such a velocity would not be tolerable at outlet openings.

5. When a room is heated wholly or chiefly by warm air, the distribution of heat in the room will be almost wholly controlled by the location of the foul-air outlets. The natural course of the air current is this: the heated air rises to the ceiling, spreads out, and coming in contact with the outer walls which are lower in temperature than the inside walls, especially the windows, it is cooled and falls to the floor. It is evident then that as the outer walls and the portions of the room adjacent to them are necessarily the coldest part of the room, the circulation of the air through the room and the proper distribution of the heat will be facilitated by placing the foul-air openings along the outer walls and preferably under the windows. If the foul-air outlets are placed in an inner wall or at the floor near an inside wall, one effect will be to draw toward this opening warm air which ought to have been utilized in warming the outer walls. Another effect, and one of the most disagreeable features attending this method of placing the foul-air outlets, is that the air which has been cooled by contact with the windows and outer walls and by its greater specific gravity has fallen to the floor, will be drawn the whole distance across the floor to the opening on the opposite side, thus constantly maintaining at the floor a stratum of cold air. An arrangement of this sort is a very frequent cause of cold floors, and consequently cold feet, and the resulting headaches from which the occupants of such a room are almost sure to suffer.

The foul-air outlets should be placed as near the floor as possible. The opening may be in the base board or in the floor itself. The only objection to the latter method is the collection of dust which is likely to be swept into the opening.

6. The ventilating ducts communicating with foul-air outlets should have a sectional area equal to the free area of the openings with which they communicate. This capacity should be maintained until the duct

reaches the ventilating shaft, and should be increased if several turns are made in the duct as each square turn has the effect to diminish the velocity of the air current nearly one-half. Square turns should never be made, and the ducts should be enlarged at the angles where a turn is necessary. In case a duct must be carried for some distance, its capacity should be increased fifty or even one hundred per cent to compensate for the great amount of friction occasioned by distance. The ventilating ducts should of course be made tight. For this purpose it is necessary that they should be lined with metal or some other durable material. Even well-seasoned lumber will shrink and open up large cracks, by which the efficiency of the duct will be very materially diminished. It is also a wise plan to construct ventilating ducts of some non-combustible material, or at least to line with such material as a caution against fire.

Only ducts coming from the same room or floor should be connected with a common ventilating shaft. Each story must have its own foul-air shaft; otherwise the counter drafts occasioned by the opening of doors and windows, especially in moderate weather, or the adverse influence of winds, will be certain to lead to contamination of the air of one room by the air of another room with which it is in communication through the common shaft.

It is of the utmost importance to supply each floor, and if possible each room, with its own independent ventilating shaft running as directly as possible to the open air without any connection with other ducts.

The location, sectional area, and height of the ventilating shaft, are questions of very great interest and practical importance. As regards location, it is always better that the ventilating shaft should when possible be located within the building, as in an inside wall; this insures a temperature equal to that within the building, and so secures a constant and positive draft, whenever the building is supplied with artificial heat. If, in addition, the vetilating shaft can be located adjacent to the chimney, or if the smoke can be carried up through it by means of a boiler iron stack or a stack constructed of sewer pipe, a still higher temperature of the air in the ventilating shaft and hence a better draft will be secured.

The sectional area of the shaft will depend upon the amount of air to be removed and the height of the shaft.

By a careful study of the tables of Parke and others, I have been able to construct a simple formula which is of great practical service in determining these two questions. The following is the formula: The square root of the height of a shaft, multiplied by the square root of the difference in temperature between the air in the shaft and the outside air, divided by four, equals the velocity of the air in the shaft in feet per second. In using this formula, it is of course necessary that two of the quantities should be known. The difference in temperature is a pretty constant factor. In fixing this the minimum difference should of course be chosen rather than the maximum, as a ventilating shaft which may have an ample capacity in extreme cold weather when the great difference between the external and internal air would secure a powerful draft, would be quite insuffcient to supply the necessary amount of air in moderate weather. I have chosen as a basis for obtaining the minimum difference in temperature, the tempertuare of 45° F. for external, and 70° F., the usual internal temperature. At a temperature much higher than 45 degrees, doors and windows are likely to be opened and hence the working of any

ventilating apparatus would be interfered with. The difference between 45° and 70° is 25, which may be fairly taken as a basis for calculation.

The height of the ventilating shaft is usually determined by the architect, who considers it with reference to the architectural effect in the building. When this is given, we have but to take the square root of the known height of the chimney, multiplied by the square root of 25 which is 5, divide the product by 4 and you have as a result the velocity at which the air will travel in the shaft in feet per second. It only remains to divide the total number of cubic feet to be removed per second by the velocity of the air per second, and the result is the sectional area of the shaft which is sought. Let us take a simple example by way of illustration. Given the height of the shaft 50 feet, and the amout of air to be furnished 72,000 cubic feet per hour or 20 ft. per second, the formula would work out thus:

$\frac{\sqrt{50}\times\sqrt{25}}{4}=$ Vel. in ft. per sec. $=9$ ft. $\frac{20}{9}=2.22$ sq. ft., the necessary sectional area of the shaft.

If the area of the ventilating shaft is given, the height being left to be determined, it is only necessary to know the amount of air to be removed, the difference between the internal and external temperatures, and to fix upon the velocity at which the air shall travel. The sectional area of the shaft must often be determined by the conveniences of construction, being governed by the plan of the building. A very safe rule is to make the sectional area of the ventilating shaft equal to the combined sectional areas of all the ducts leading into it. It is possible to secure efficient ventilation with a ventilating shaft which is somewhat smaller than this, but this is unquestionably the safest rule to follow. To determine the rate at which the air will travel, it is only necessary to divide the amount of air in cubic feet required per second, by the sectional area of the shaft expressed in feet. With these data the determining of the required height is a very simple problem, using the formula which has already been given. An example will make this entirely clear.

Let us suppose that the conditions are as follows: air is required for 48 students. At 2,400 cubic feet per hour for each, the total amount needed would be 115,200 cubic feet per hour, or 32 cubic feet per second. The combined area of ducts of sufficient size to allow the transmission of this air at the rate of 5 feet per second would be $32\div5=6.4$ square feet, and the velocity will of course be 5 feet. The question we have to solve is what would be the necessary height of the ventilating shaft to secure this velocity, the difference in temperature being 25°F. The solution of this very practical problem is extremely simple. Bearing in mind the formula we will let H represent the height of the shaft, D the difference between the internal and external temperatures, and V the velocity of air per second; $\frac{\sqrt{H}\times\sqrt{D}}{4}=V$. Substituting the quantities which are known we have the following: $\frac{\sqrt{H}\times\sqrt{25}}{4}=5$. Reducing we have $5\sqrt{H}=20$; $\sqrt{H}=4$; $H=16$; that is, the height of the shaft required by the conditions named would be 16 feet. In most instances it is more convenient to employ a smaller shaft and one of greater height. Let us suppose such a case, in which the amount of air required per second is the same, namely, 32 cubic feet per second, and the sectional area of the shaft 4 square feet instead of 6. Dividing the amount of air required per second by the area of the shaft we have

8 as the velocity per second $(32 \div 4 = 8.)$ Our formula then would be as follows: $\frac{\sqrt{H} \times \sqrt{25}}{4} = 8$ reducing we have $5\sqrt{H} = 32$; $\sqrt{H} = 6.4$; $H = 40.96$. In this case the height of the shaft would be practically 41 feet. By the same method the necessary height of shaft for any given area may be readily determined.

From an economical standpoint, other things being equal, it is far better to secure increased efficiency by increasing the size of the ventilating shaft rather than its height, for the obvious reason that the capacity of a shaft for removal of air increases directly with the increase in sectional area; whereas the velocity of the air current increases in direct ratio with the square roots of the heights of the shaft, thus requiring that the height of a shaft shall be quadrupled to double its efficiency, while it is only necessary to double its sectional area to secure double efficiency. There is also a loss by increase of friction and of cooling surface, and in the disproportionate increase of expense of construction. The cost of increasing the efficiency of a shaft one hundred per cent, by increasing the velocity of the air current, will be very much greater than in securing the same result by increasing its sectional area.

Cases occur, of course, in which the stronger draft secured by increased height of shaft is essential to the efficient working of a ventilating system, or the accomplishment of a specific purpose.

8. When possible to do so it is unquestionably preferable to so plan a system of heating and ventilation that it will operate efficiently by the aid of "natural draft" only. Such a system is as nearly automatic in its action as any ventilating system can be made. A draft which depends upon a mechanical apparatus, as a pressure or suction fan, or even upon a steam coil or other form of heating apparatus in the ventilating shaft, is very likely to be found defective when efficiency is most needed. I have visited many large institutions provided with large ventilating fans, and have never yet found one in which the apparatus was in constant operation. In many cases it had been inoperative for years and was not in running order. In one case I was informed that the fan was started "whenever the odors in the ward became so strong as to be very noticeable." To my nose the odors were at that moment very strongly pronounced, and yet the fan was not in operation. The noses of managers and attendants become accustomed to odors to the presence of which they are constantly exposed, so that they cease to be a proper means of testing the condition of the air.

Some years ago the writer visited a large hospital, the air supply of which, was wholly dependent upon a fan which was a pressure blower, and hence so constructed that when the fan was not in operation the opening for the entrance of air through the fan was very small. The fan was placed in the mouth of a tunnel nearly eight feet in diameter, just about the proper size for supplying air to the hospital at a moderate velocity, but the opening from the fan had a sectional area of only about four square feet. The hospital had been in operation for some three years. The fan had never been in operation since the opening day, as it was run by a separate engine and was so far from the building as to require the attention of a special engineer when in use, and consequently the air supply of the hospital, which was filled with sick people of all classes, was limited to the small opening described, there being no other. It is certainly unwise to so plan the ventilating system of a large building as to make the inmates absolutely dependent upon the efficient working of a

mechanical apparatus of this sort. Mechanical and other means of assisting "natural draft" are, nevertheless, valuable and, in some instances, necessary accessories to a system of natural ventilation, especially for large buildings, as they furnish a means by which the disturbing influence of winds may be more or less completely overcome. The writer has had two large fans in use in buildings under his care for several years, as occasion has required. As usually constructed and employed, however, these appliances are almost useless from their inadequacy and inefficiency. This is especially the case when heat in the ventilating shaft is depended upon as the means of securing a strong draft, in consequence of the use of an amount of heating surface quite inadequate for the work required.

Ventilating shafts which are exposed on all sides, and even those which are placed in the outer walls of buildings, must be heated or furnished with a fan to insure a constant draft. The amount of heating surface usually provided in such cases is ridiculously small, and is not infrequently so placed as to be of very little value. When it is recalled that all the air supplied to a building must pass through the ventilating shaft it will be apparent that a considerable amount of heat must be imparted to this air to produce a strong draft in case the chimney is so situated that the air loses a considerable amount of its heat before it is expelled from the chimney.

From experiments which have been made (Box) for the purpose of determining the heating capacity of steam pipes we know that one square foot of surface of one-inch pipe (3 linear feet) will give off about 300 heat units per hour, or 5 heat units per minute under the conditions in which heating is required in a ventilating shaft. Five heat units will raise the temperature of 276 cubic feet of air 1° (1 cubic foot of air at 62° weighs .0761 lbs. The specific heat of air is .238. $5 \div .0761 \div .238 = 276$). Knowing the amount of air to be transmitted by the ventilating shaft per minute or second, it is easy to determine the amount of heating surface required to raise the temperature of the air one or more degrees. It is only necessary to divide the amount of air transmitted per minute by 276 to determine the number of square feet of heating surface required to raise the temperature of the given quantity of air 1° F.

Taking, for example, a case in which, as in our last illustration, the amount of air required to be transmitted is 32 cubic feet per second, or 1920 cubic feet of air per minute, we have $1920 \div 276 = 6.95$, practically 7 square feet of heating surface, or 21 linear feet of one-inch pipe, necessary to raise the temperature of the air 1° F. To raise the temperature of the air 5°, which would be quite sufficient to insure the successful working of the shaft, would of course require five times as much heating surface, or 105 linear feet of one-inch pipe.

The most economical method possible for heating a ventilating shaft is the combustion of fuel in the shaft itself. A number of years ago in studying the ventilation of the House of Parliament in London, by the aid of the assistant engineer who kindly conducted me through the subterranean region of this great structure, I was surprised to find that the current of air in the great towers, which are not merely architectural features but constitute the ventilating shafts of the building, was maintained by means of a great heap of burning coal which was placed exactly in the center of the shaft upon a high platform, the top of which was at about

the same level as the top of the great horizontal ventilating ducts which entered the shaft at its bottom.

Fuel may be consumed in a shaft by means of a stove placed in a chimney, carrying the stovepipe up through it. In exceptional cases the smoke may be discharged directly into the shaft; but this arrangement is not always a safe one and hence cannot be recommended. The position of the heater is a matter of no small importance. I have sometimes seen a steam coil placed at the extreme bottom of the ventilating shaft, the first opening being several feet above it. In so placing the heater there is very little circulation of air, and hence its efficient heating capacity is not utilized. To secure the efficient working of a ventilating shaft the heater should be placed above the highest opening. It is, as a rule, not wise to have openings into a ventilating shaft at different levels, but if this arrangement cannot be avoided, the heater should certainly be placed above the highest opening; or if a long heater, placed against the side of the chimney, it should extend above the highest opening. Whether the heat should be concentrated near the lower portion of the shaft, or should be extended some distance along the inside wall, is a question which may be differently answered according to circumstances. There is an advantage in the extension of the heater some distance along the inner wall in that a better opportunity is afforded for radiation, and thus for heating the inner surface of the shaft, and so preventing the tendency to downward currents. It should be remembered, however, that the higher in the shaft the heater is placed the shorter will be the heated column, and hence, from this standpoint, the less the efficiency of the heat employed.

In conclusion, the writer wishes to disavow any attempt to make, in the foregoing, an extensive presentation of the subject of ventilation. Those who wish to make an extended study of the subject will find the means of doing so in the excellent work of Mr. Thomas Box, published by E. and F. N. Spon, 12 Cortlandt street, New York city. My aim in the preparation of this paper has been to present such practical points as I have gathered from a somewhat extended experience in planning the ventilation of large buildings in which I have had an opportunity to live for a series of years studying the result of various methods employed, and to formulate a few simple rules which are useful for the working out of correct methods of ventilation in all ordinary cases, and which are much less cumbersome for use than the ponderous formulæ of Box and others who have undertaken to present this subject in a scientific way. I ought also, perhaps, to call attention to the fact that, while the physical principles relating to heating, ventilating, etc., are correctly given by Box and other authors who have given much scientific data upon this subject, the suggestions made with reference to the supply of fresh air are, as a rule, widely at variance with the conclusions at which Parke, Angus Smith, and other investigators have arrived in the study of the question of ventilation from a sanitary and hygienic standpoint, and so are not to be relied upon. For example, Box puts the amount of fresh air required for each person per hour at 212 cubic feet, which is simply ridiculous, being less than one tenth the amount shown by ample experience to be really necessary.